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Price et al.

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(54) **SYSTEMS AND METHODS FOR ELECTRON BEAM FOCUSING IN ELECTRON BEAM ADDITIVE MANUFACTURING**

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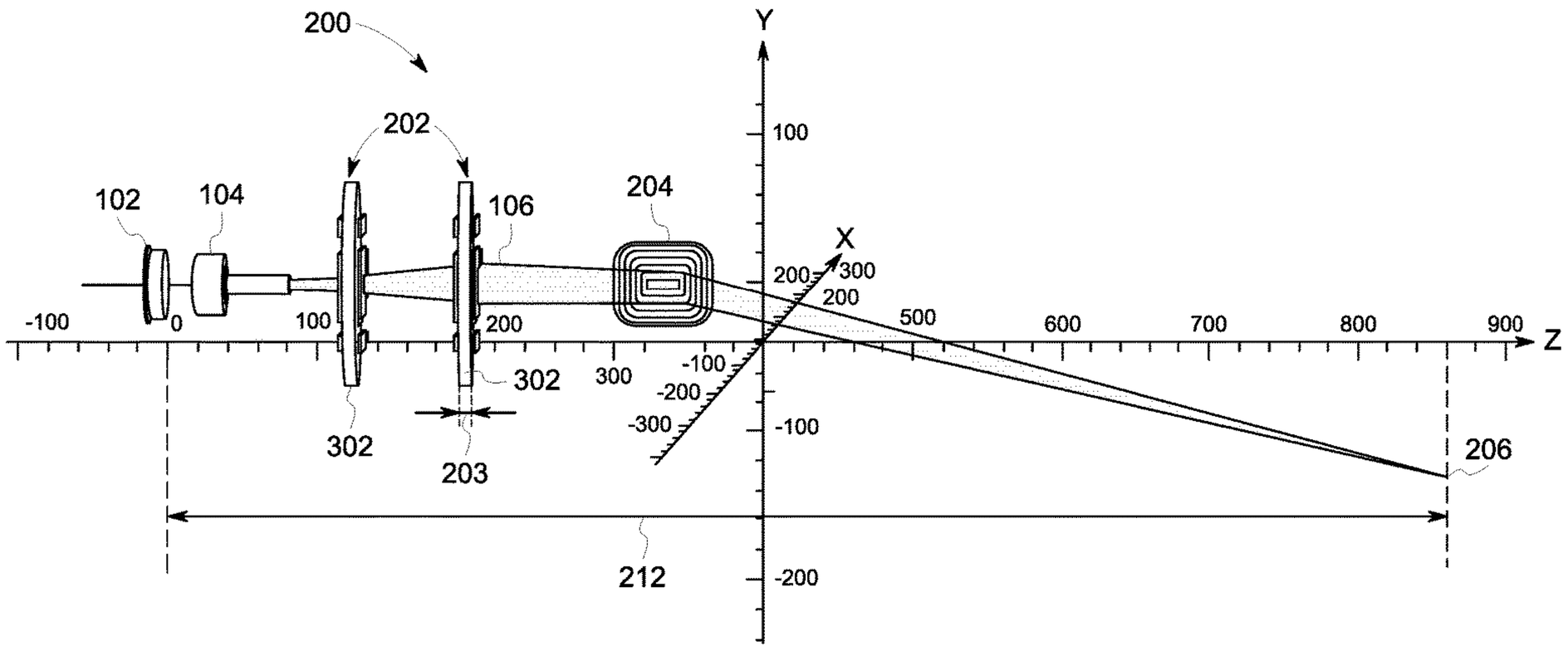
(57) **ABSTRACT**

A system for melting, sintering, or heat treating a material is provided. The system includes a cathode, an anode, and a focus coil assembly having a quadrupole magnet. The quadrupole magnet includes four poles and a yoke. The four poles are spaced apart and surround a beam cavity. Each of the four poles includes a pole face proximate the beam cavity and an end opposite the pole face. The first and third poles are aligned along an x-axis and configured to have a first magnetic polarity at their respective pole faces and a second magnetic polarity opposite the first magnetic polarity at their respective ends. The second and fourth poles are aligned along a y-axis and configured to have the second magnetic polarity at their respective pole faces and the first magnetic polarity at their respective ends. The yoke surrounds the poles and is coupled to the poles.

14 Claims, 13 Drawing Sheets



(51) **Int. Cl.**

B29C 64/153	(2017.01)
B29C 64/273	(2017.01)
H01J 37/305	(2006.01)
B33Y 30/00	(2015.01)

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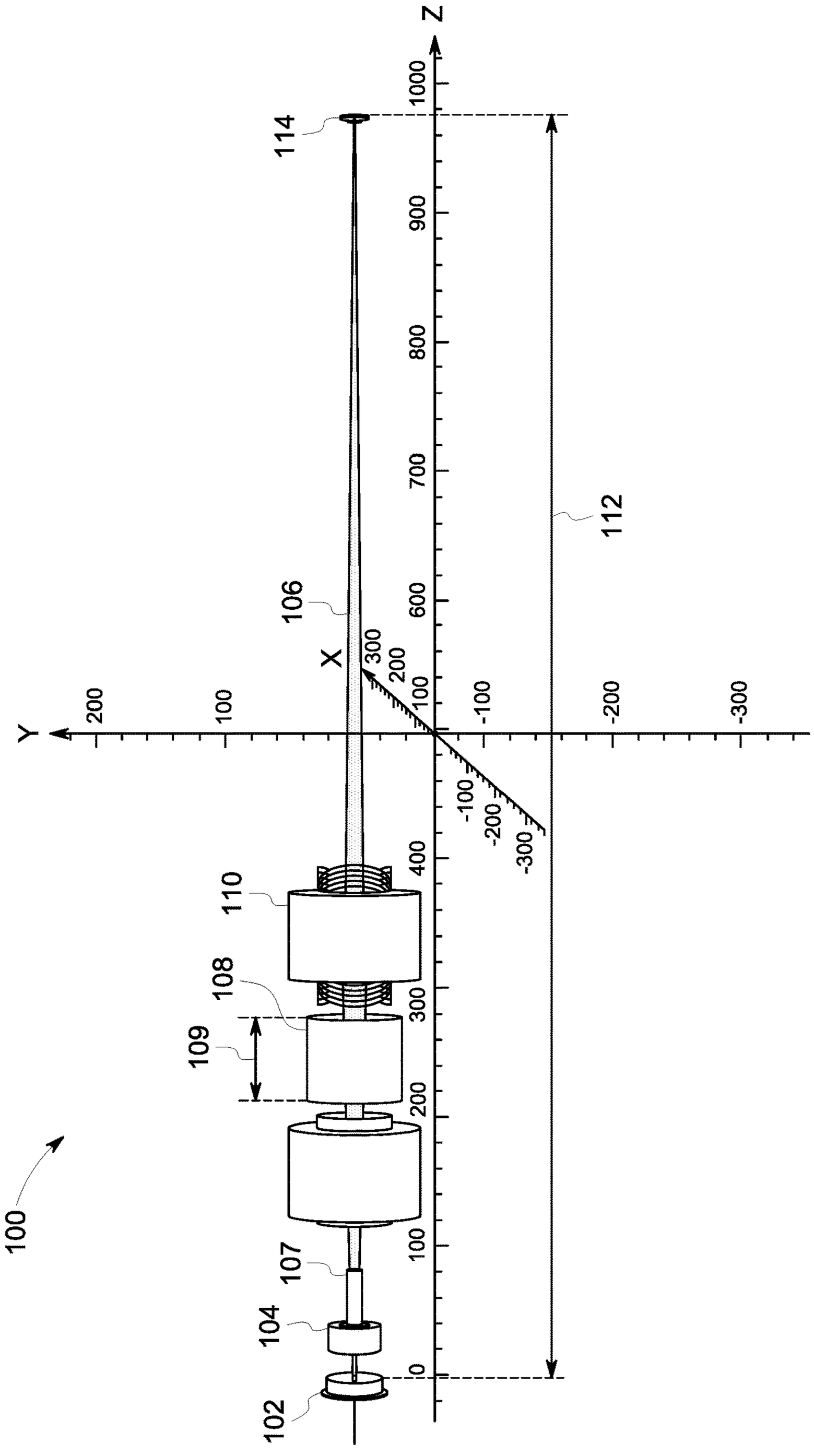


(Prior Art)
FIG. 1

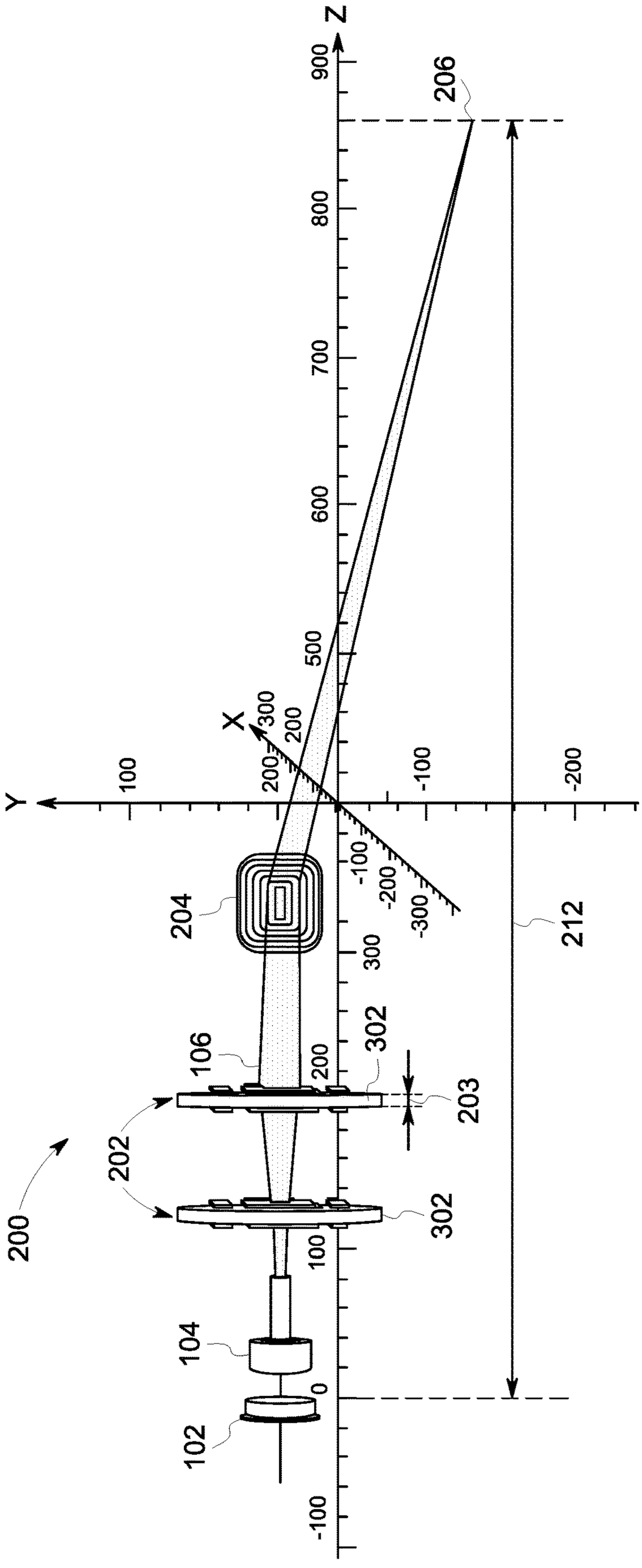
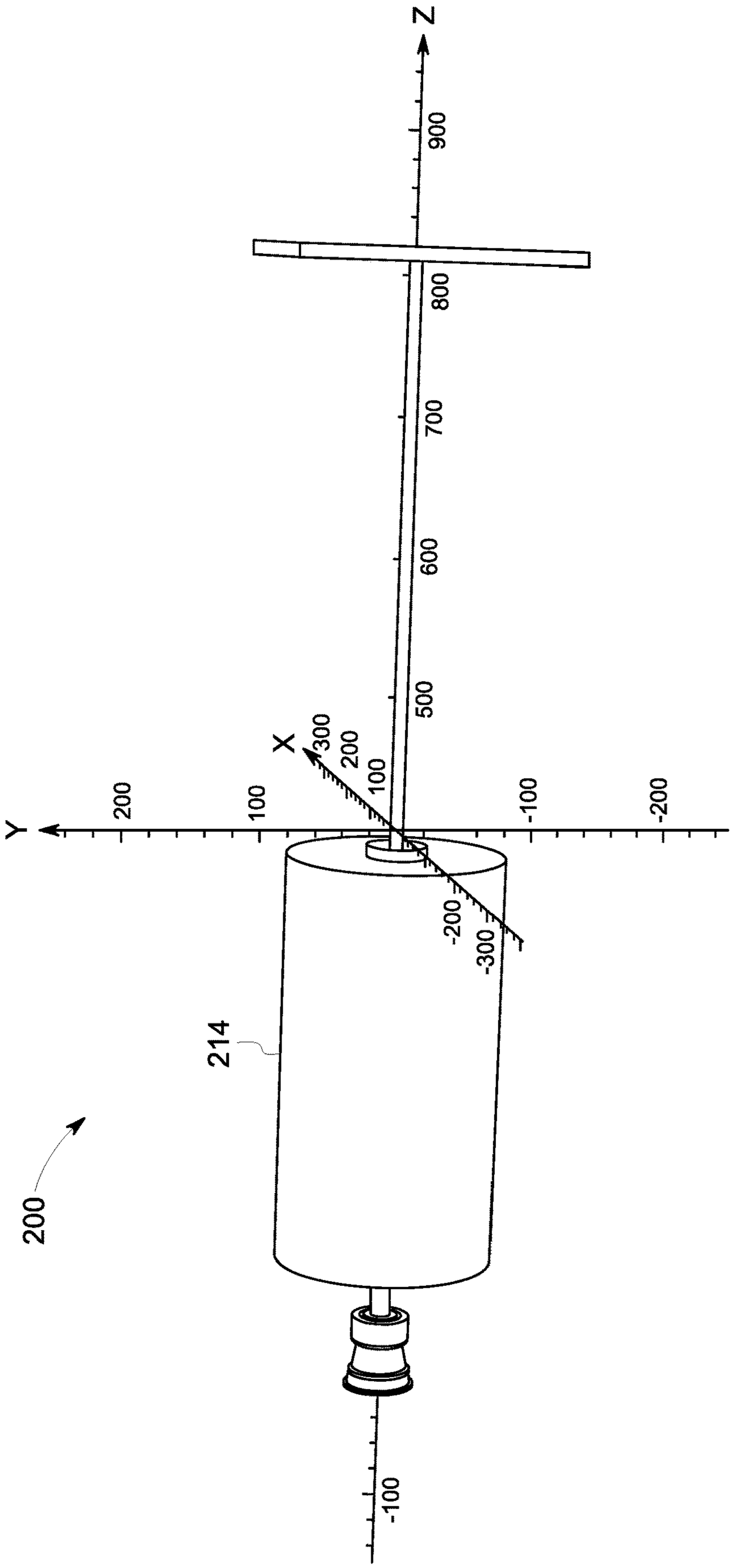

Z
900
800
700
600
500
206
Y
100
X
300
200
200
-100
-200
-100
-200
-300
204
212
300
106
200
302
203
202
302
200
100
104
0
102
-100

FIG. 2A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-300
Y
200
100
-200
214
200
-100

FIG. 2B

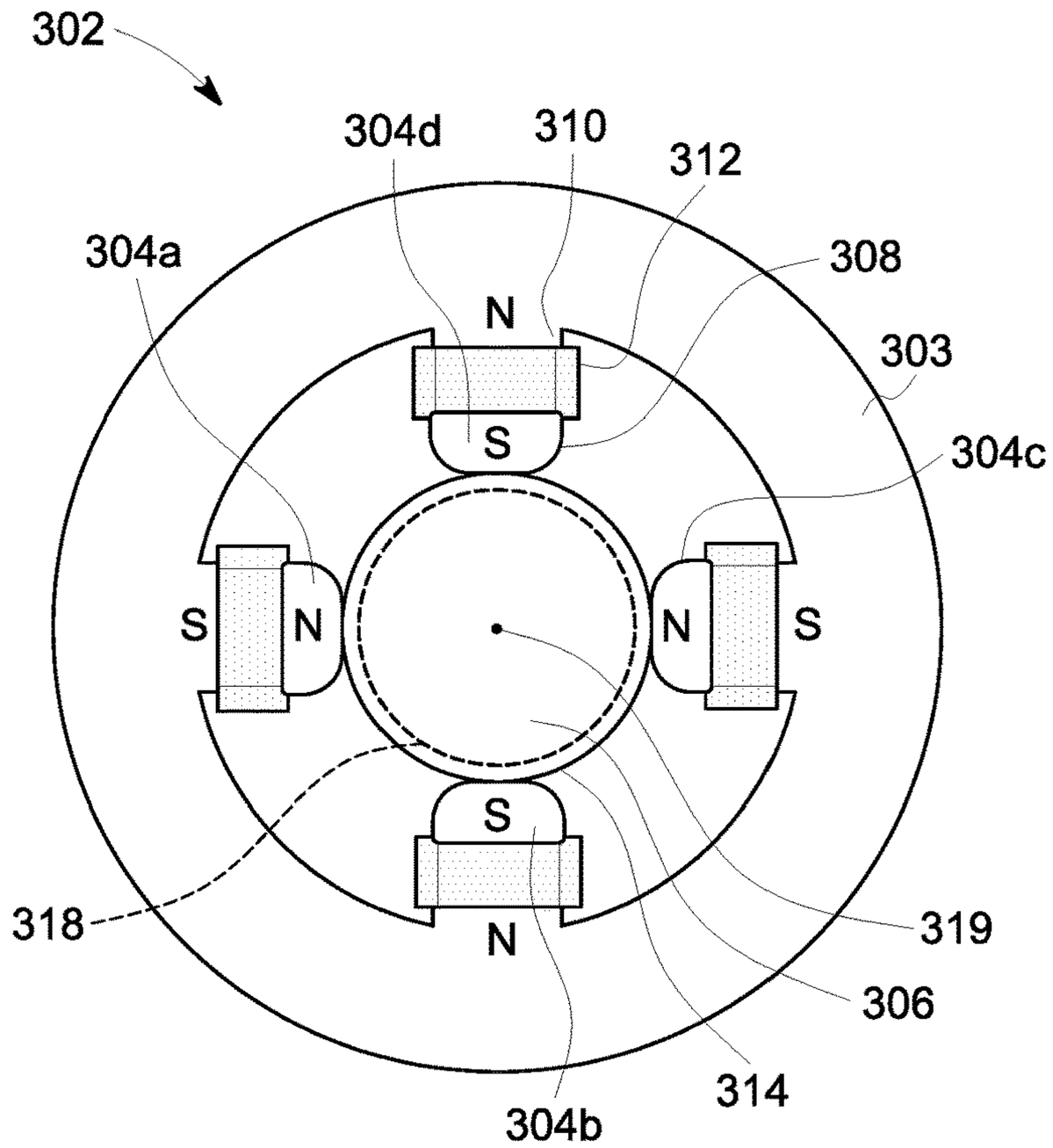
302
304d
310
312
304a
308
303
304c
N
S
S
N
N
S
S
N
318
319
306
314
304b

FIG. 3A

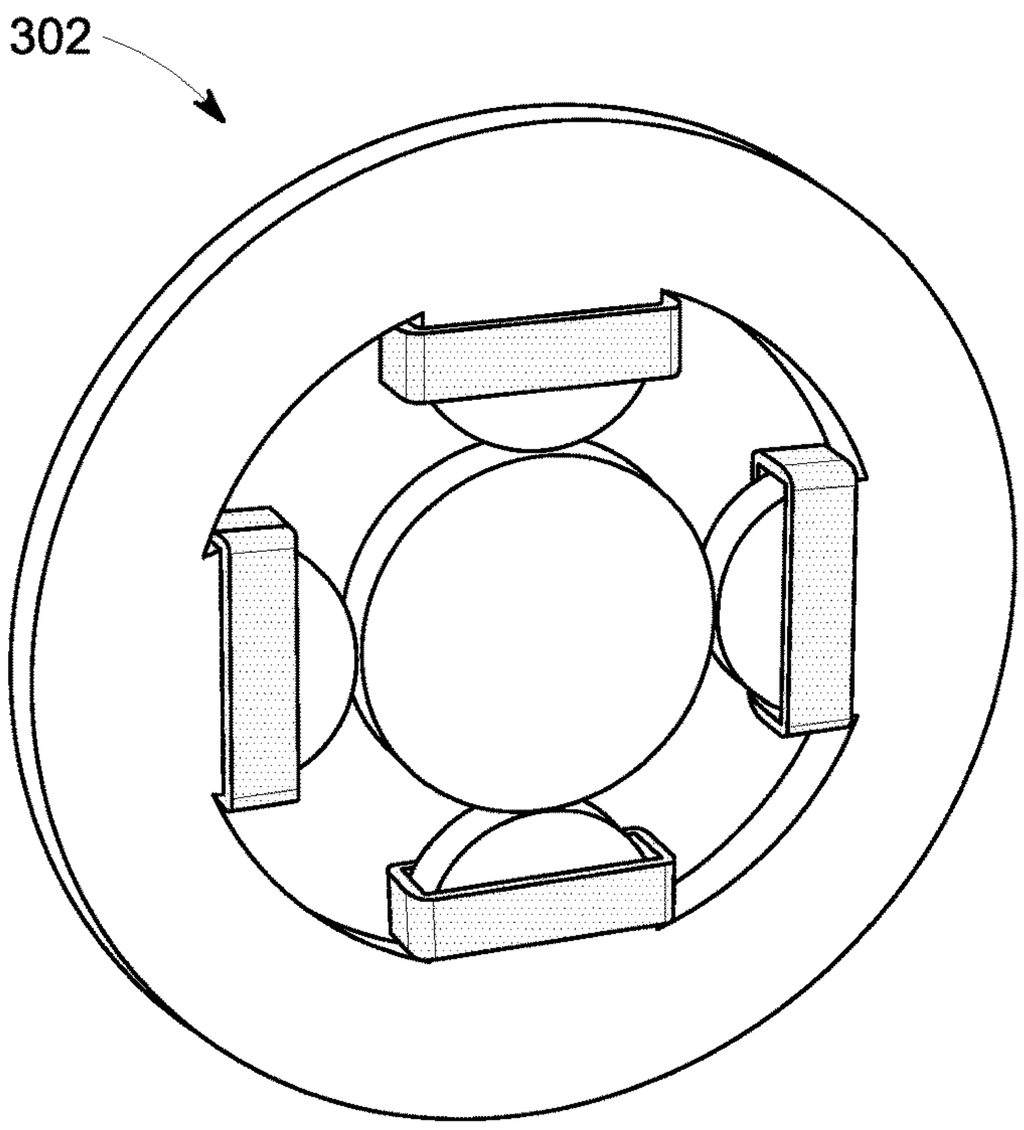
302

FIG. 3B

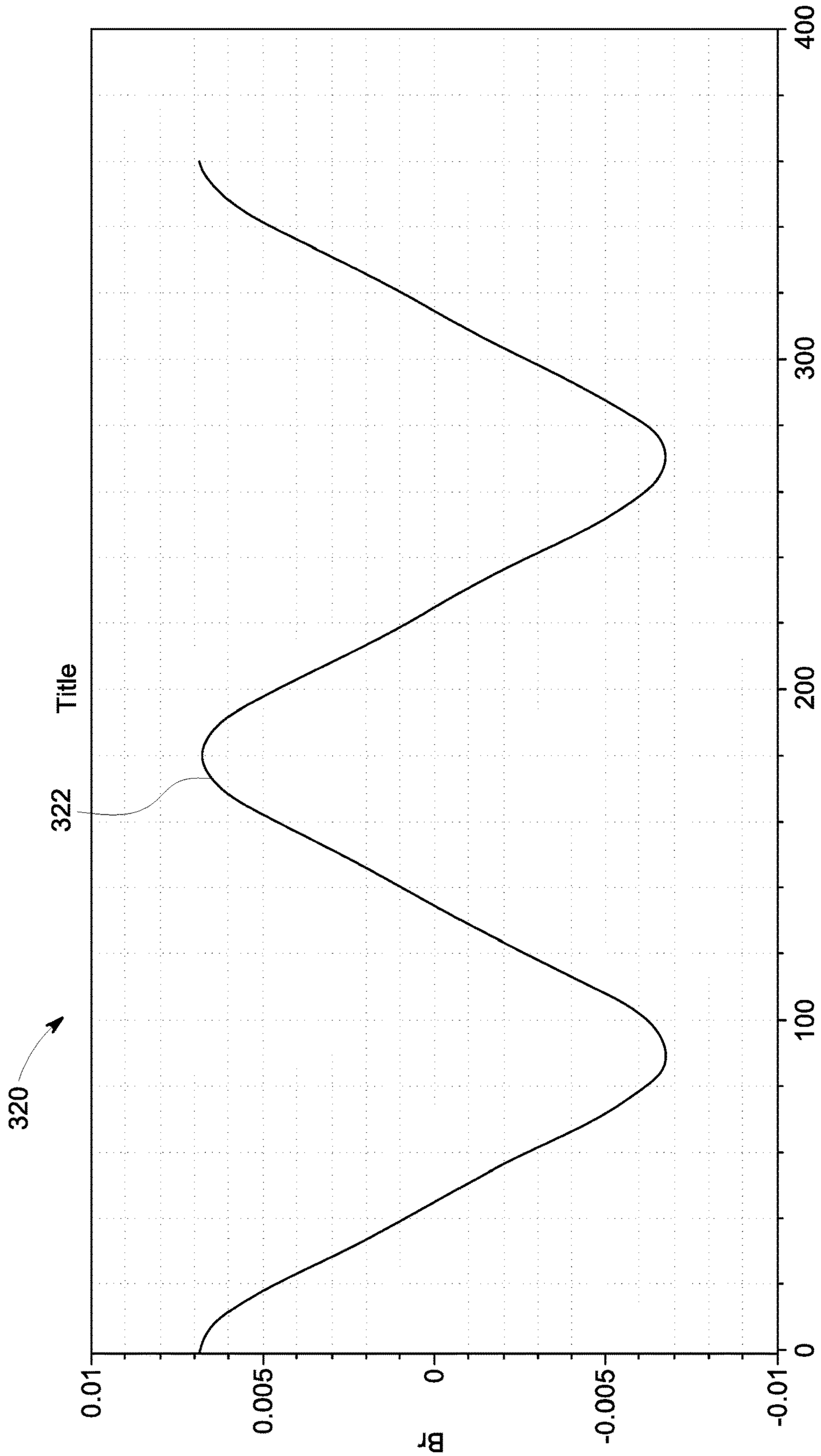

FIG. 3C

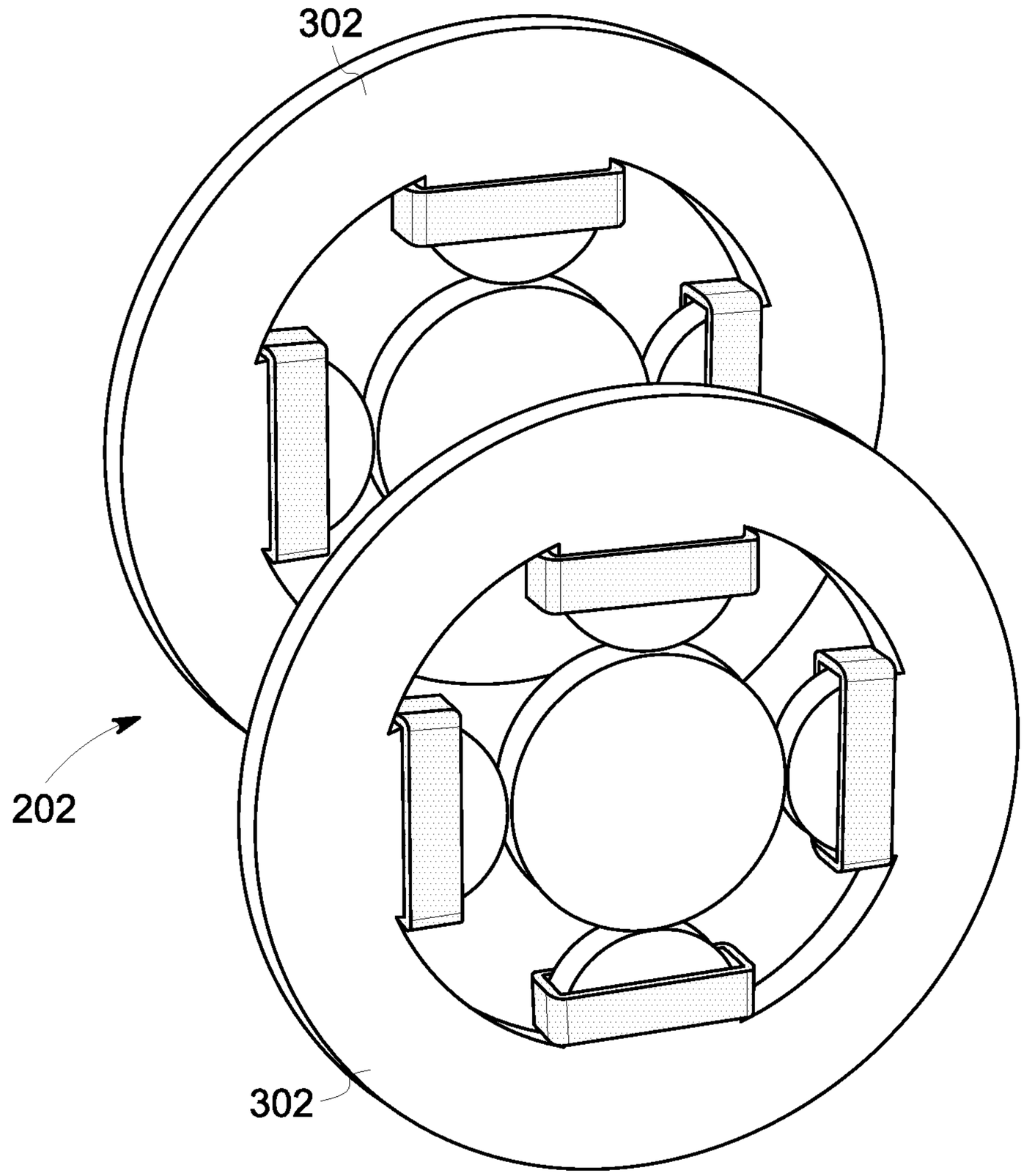

FIG. 4A

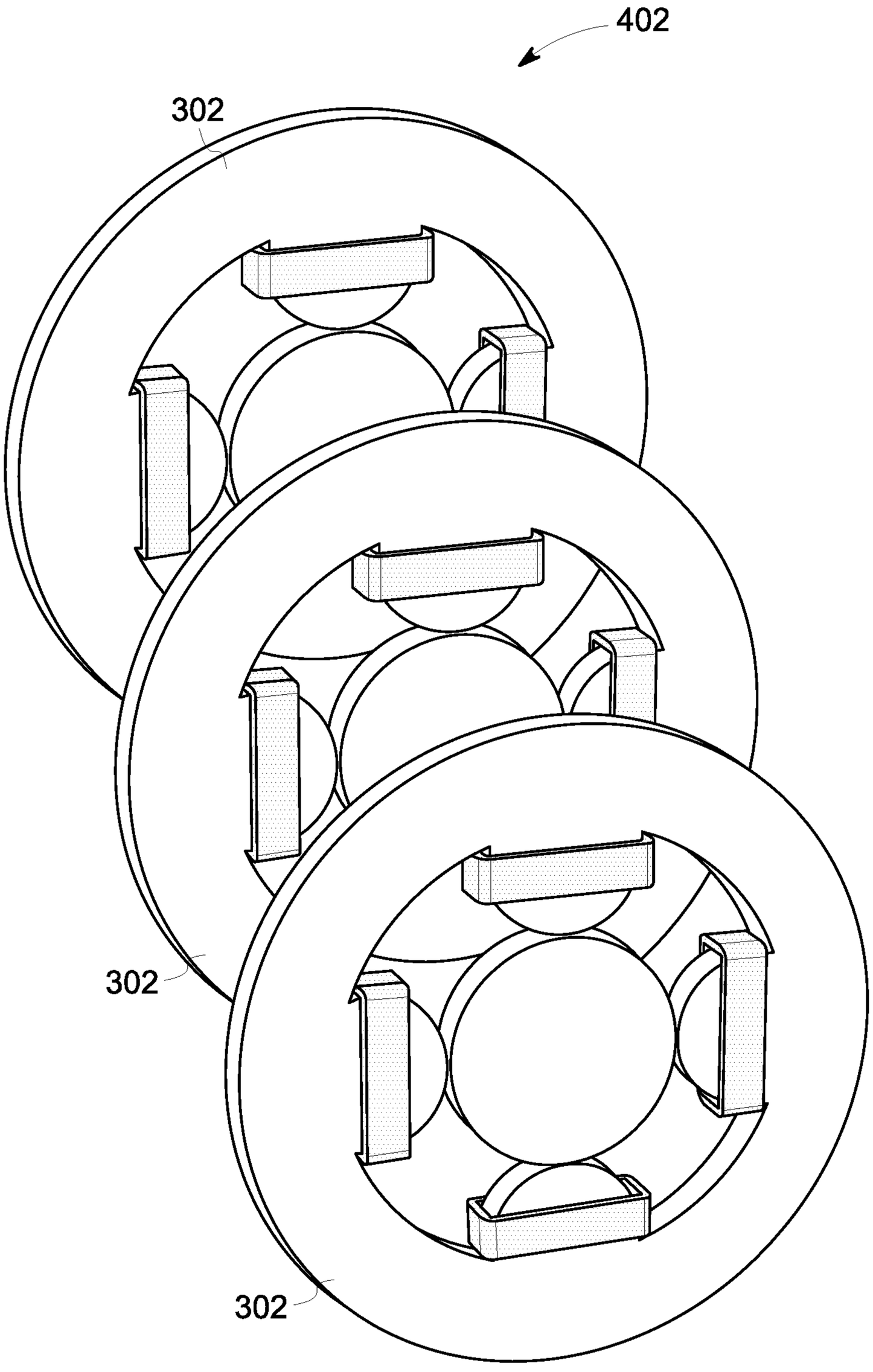

FIG. 4B

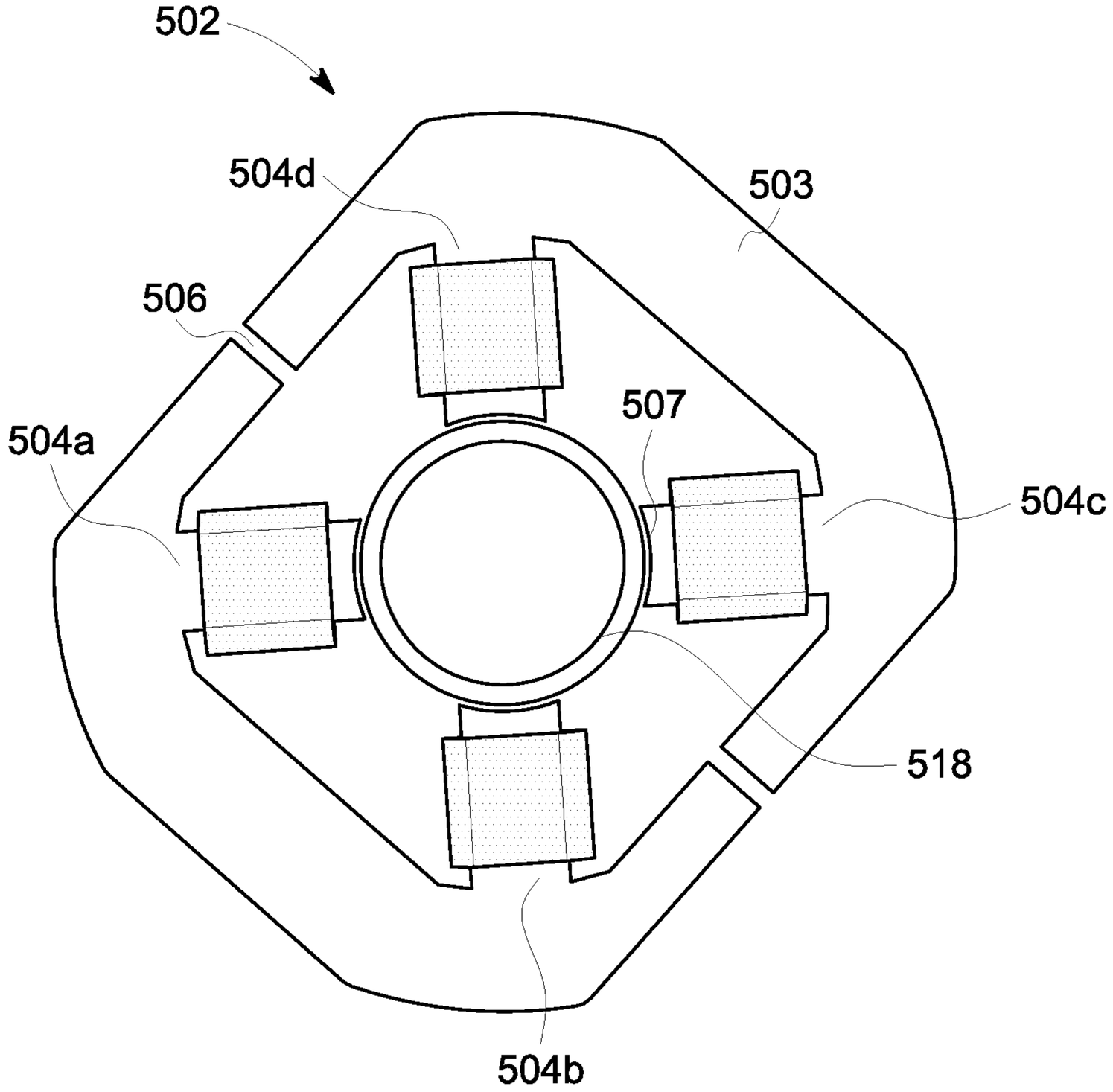

FIG. 5A

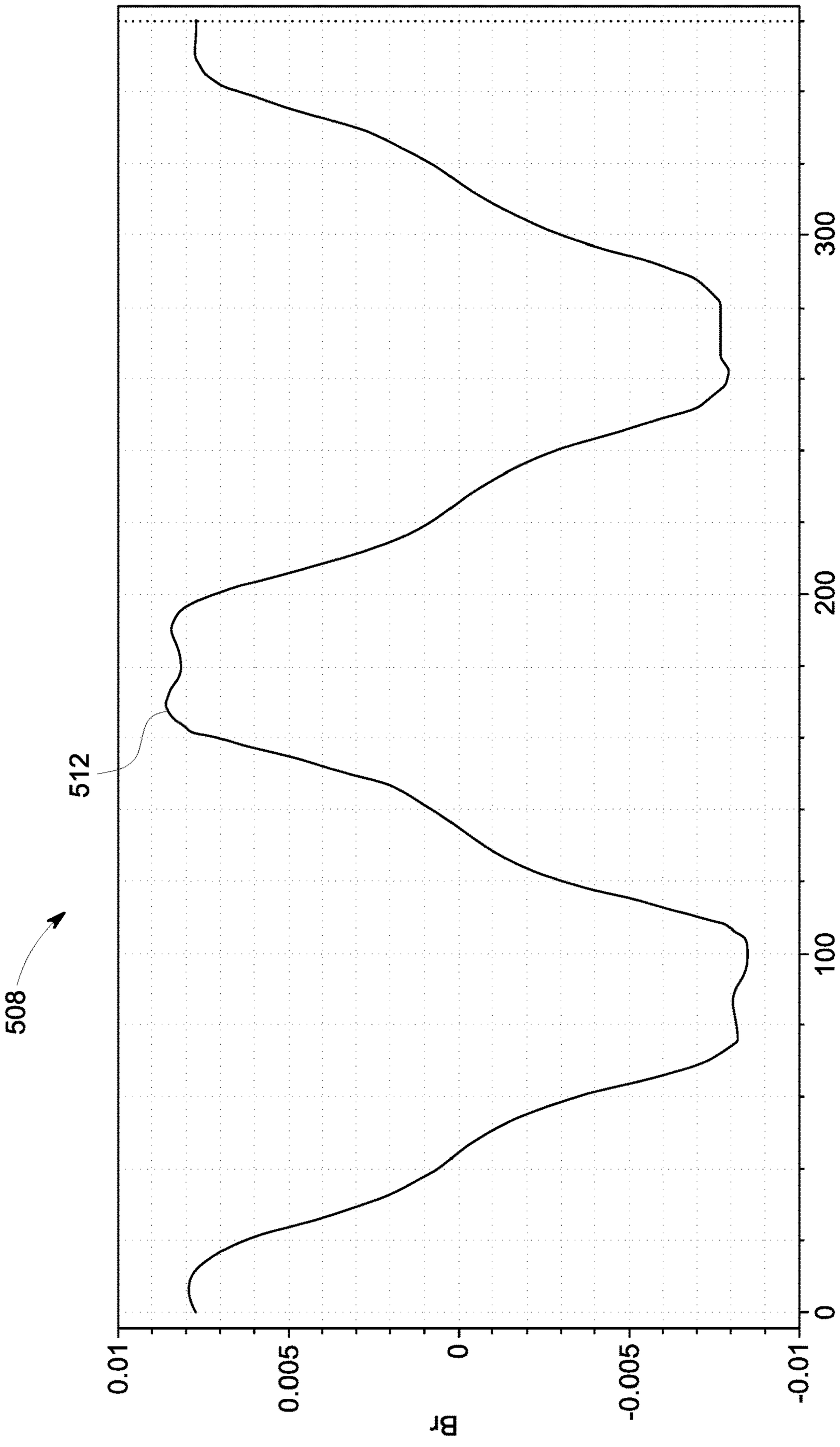

FIG. 5B

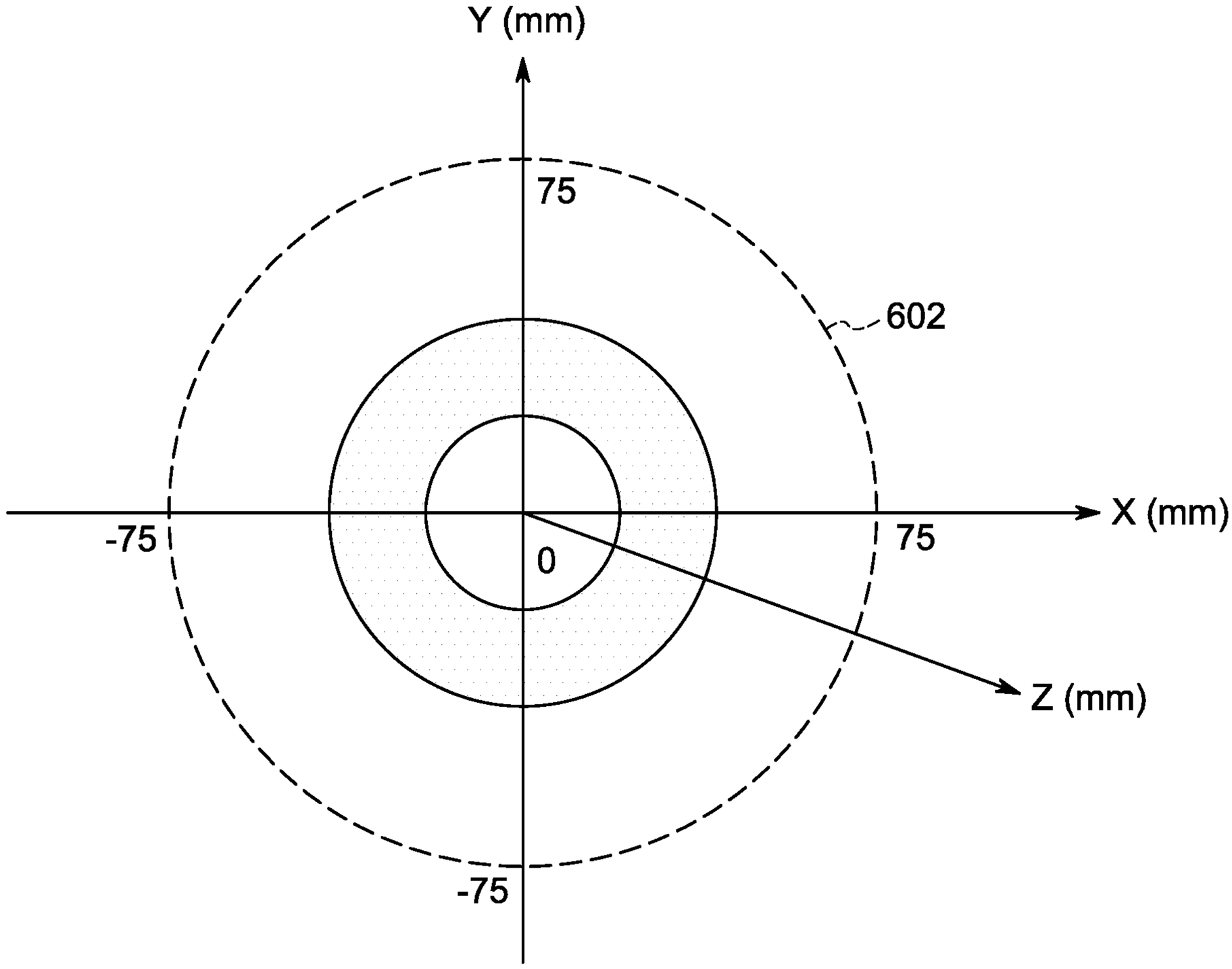

FIG. 6A

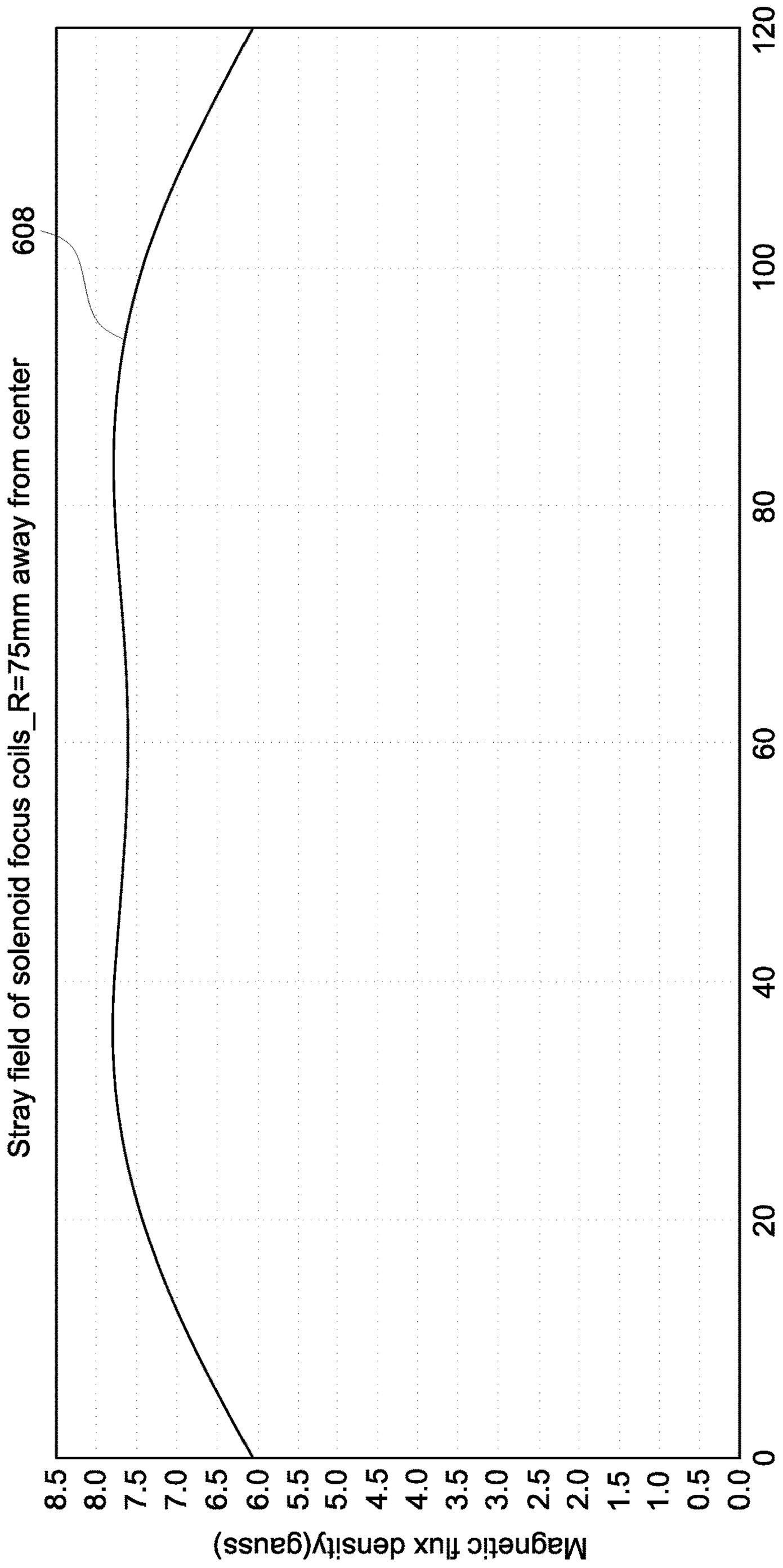
Stray field of solenoid focus coils_R=75mm away from center
608
Magnetic flux density(gauss)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
120
Z(mm)

FIG. 6B

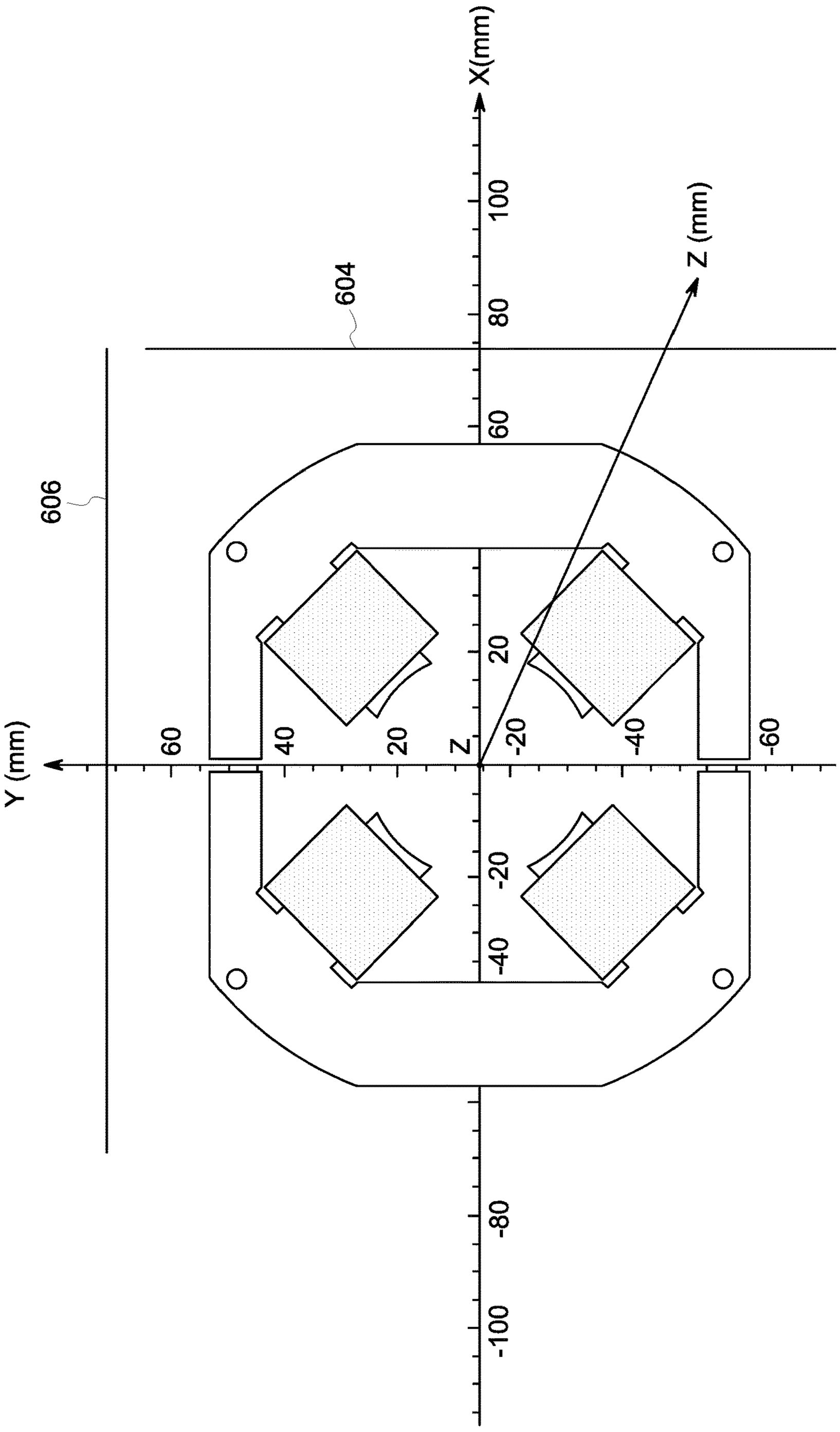

FIG. 6C

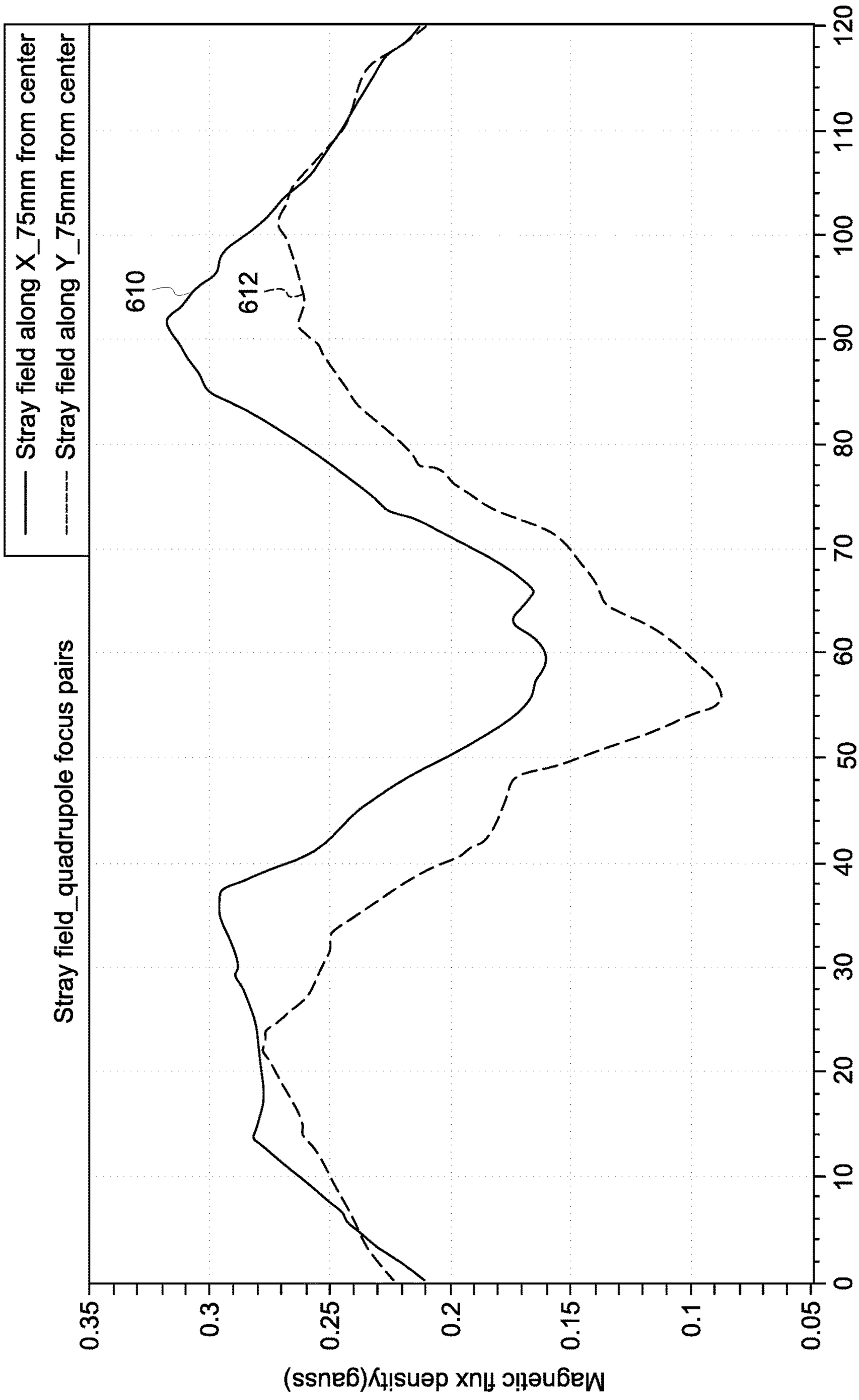
Stray field along X_75mm from center
Stray field along Y_75mm from center
610
612
Stray field_quadrupole focus pairs
Magnetic flux density(gauss)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10
20
30
40
50
60
70
80
90
100
110
120
Distance (mm)

FIG. 6D

SYSTEMS AND METHODS FOR ELECTRON BEAM FOCUSING IN ELECTRON BEAM ADDITIVE MANUFACTURING

BACKGROUND

The field of the disclosure relates generally to systems and methods of electron beam additive manufacturing, and more particularly, to systems and methods of focusing and steering an electron beam using a focus coil assembly having a quadrupole magnet in an electron beam additive manufacturing system.

Electron beam additive manufacturing or electron-beam melting (EBM) is a type of additive manufacturing or 3D printing, for metal parts. In EBM, an electron beam is used as a heating source to fuse raw material, such as metal powder or wire, under a vacuum. The electron beam is controlled by a focus coil assembly, which focuses the electron beam with a magnetic field such that the electron beam has a profile with a desired diameter and shape. However, the magnetic field may extend beyond the focus coil assembly, causing a stray field that affects the electron beam after exiting from the focus coil assembly.

At least some known focus coil assemblies are prone to certain problems, and improvements in focus coil assemblies are desirable.

BRIEF DESCRIPTION

In one aspect, a system for melting, sintering, or heat treating a material is provided. The system includes a cathode, an anode, and a focus coil assembly. The cathode and the anode are configured to generate an electron beam. The focus coil assembly includes a quadrupole magnet. The quadrupole magnet includes first, second, third, and fourth poles and a yoke. The first, second, third, and fourth poles are spaced apart from each other and surround a beam cavity through which the electron beam travels. Each of the first, second, third, and fourth poles includes a pole face proximate the beam cavity and an end opposite the pole face. The first and third poles are aligned along an x-axis and configured to have a first magnetic polarity at their respective pole faces and a second magnetic polarity opposite the first magnetic polarity at their respective ends. The second and fourth poles are aligned along a y-axis and configured to have the second magnetic polarity at their respective pole faces and the first magnetic polarity at their respective ends. The x-axis is perpendicular to the y-axis. The yoke surrounds the first, second, third, and fourth poles and is coupled to the first, second, third, and fourth poles at the ends of the first, second, third, and fourth poles.

In another aspect, a focus coil assembly for melting, sintering, or heat treating a material is provided. The focus coil assembly includes a quadrupole magnet. The quadrupole magnet includes first, second, third, and fourth poles and a yoke. The first, second, third, and fourth poles are spaced apart from each other, and surround a beam cavity through which the electron beam travels. Each of the first, second, third, and fourth poles includes a pole face proximate the beam cavity and an end opposite the pole face. The first and third poles are aligned along an x-axis and configured to have a first magnetic polarity at their respective pole faces and a second magnetic polarity opposite the first magnetic polarity at their respective ends. The second and fourth poles are aligned along a y-axis and configured to have the second magnetic polarity at their respective pole faces and the first magnetic polarity at their respective ends. The x-axis is perpendicular to the y-axis. The yoke surrounds the first, second, third, and fourth poles and is coupled to the first, second, third, and fourth poles at the ends of the first, second, third, and fourth poles.

In yet another aspect, a deflection coil for electron beam additive manufacturing is provided. The deflection coil includes a quadrupole magnet. The quadrupole magnet includes first, second, third, and fourth poles and a yoke. The first, second, third, and fourth poles are spaced apart from each other, and surround a beam cavity through which electron beam travels. Each of the first, second, third, and fourth poles has a pole face proximate the beam cavity and an end opposite the pole face. The first and third poles are aligned along an x-axis, the second and fourth poles aligned along a y-axis. The x-axis is perpendicular to the y-axis. The yoke surrounds the first, second, third, and fourth poles and is coupled to the first, second, third, and fourth poles at the ends of the first, second, third, and fourth poles. The quadrupole magnet is configured to generate a dipole magnetic field.

DRAWINGS

FIG. **1** is a schematic diagram of a known electron beam additive manufacturing or electron beam melting (EBM) system.

FIG. **2**A is a schematic diagram of an exemplary EBM system according to the systems and methods disclosed herein.

FIG. **2**B is a schematic diagram of the EBM system shown in FIG. **2**A including a shielding.

FIG. **3**A is a cross-sectional view of an exemplary quadrupole magnet that may be used with the EBM system shown in FIG. **2**A.

FIG. **3**B is a perspective view of the quadrupole magnet shown in FIG. **3**A.

FIG. **3**C is a plot of a magnetic field generated by the quadrupole magnet shown in FIG. **3**A.

FIG. **4**A is a schematic diagram showing a focus coil assembly having two of the quadrupole magnets shown in FIG. **3**A.

FIG. **4**B is a schematic diagram showing a focus coil assembly having three of the quadrupole magnets shown in FIG. **3**A.

FIG. **5**A is a cross-sectional view of another exemplary quadrupole magnet that may be used with the EBM system shown in FIG. **2**A.

FIG. **5**B is a plot of the magnetic field generated by the quadrupole magnet shown in FIG. **5**A.

FIG. **6**A is a schematic diagram illustrating measurement of a stray field of a known focus coil assembly in the EBM system shown in FIG. **1**.

FIG. **6**B is a plot showing the measured stray field of the known focus coil assembly in the EBM system shown in FIG. **1**.

FIG. **6**C is a schematic diagram illustrating measurement of a stray field of the quadrupole magnet shown in FIG. **5**A.

FIG. **6**D is a plot showing the measured stray field of the quadrupole magnet shown in FIG. **5**A.

DETAILED DESCRIPTION

The disclosure includes systems and methods of focusing and steering an electron beam for an electron beam additive manufacturing or electron beam melting (EBM) system. In an EBM system, a focus coil assembly is used to focus the electron beam to have a profile with a diameter and shape.

As used herein, the profile of the electron beam refers to the cross-sectional profile of the electron beam. In some embodiments, the profile may be elliptical. In other embodiments, the profile may be circular (e.g., for fusing raw material). Further, a focus coil assembly is used to reduce a stray magnetic field, because any stray magnetic field outside of the focus coil assembly may affect the profile and travel direction of the electron beam. The focus coil assemblies disclosed herein include quadrupole magnets having a yoke and result in a reduced stray field, compared to at least some known focus coil assemblies. In the embodiments described herein, electron beam additive manufacturing is used as an example. The systems disclosed herein may be applied in any system that uses electron beams to melt, sinter, and/or heat treat materials such as metal.

FIG. **1** is a schematic diagram of a known EBM system **100**. The system **100** includes a cathode **102** and an anode **104**. The cathode **102** and the anode **104** together are configured to generate an electron beam **106**. The cathode **102** is heated to generate the electron beam **106**. A voltage difference between the cathode **102** and the anode **104** accelerates the electron beam **106** away from the cathode **102** and towards the anode **104**. The anode **104** may further include a beam tunnel **107**, along which the electron beam **106** travels. Throughout this disclosure, the axis along which the electron beam **106** travels is denoted as a z-axis, and a plane substantially perpendicular to the z-axis is denoted as an x-y plane with an x-axis substantially perpendicular to a y-axis.

The system **100** further includes a focus coil assembly **108**. The focus coil assembly **108** includes a solenoid magnet for focusing the electron beam **106**. The solenoid magnet includes wires that wind around an air-core and generate a magnetic field by conducting electricity through the wires. A length **109** of the focus coil assembly **108** along the z-axis is approximately 100 mm, when the focal length is 750 mm for focusing an electron beam having energy of 60 kilo-electronvolt (keV) with an operation current of 3 Ampere (A) provided to the wires. A focal length is the distance along the z-axis from an end of the focal coil assembly proximate to the anode **104** to a focus produced at a build plate (e.g., at a focused position **114**). The focus coil assembly **108** produces a large amount of stray magnetic field outside of the space that the electron beam **106** travels through. The system **100** further includes a deflection coil **110** configured to steer the electron beam **106** in a certain direction to enter a vacuum chamber (not shown) where parts are manufactured using the EBM process with the electron beam **106** heating raw material and fusing the heated raw material together. The distance **112** the electron beam **106** travels is approximately 1000 millimeter (mm) from the cathode **102** to a focused position **114** of the electron beam **106** in the vacuum chamber. Accordingly, the system **100** generally has a length at least greater than 1000 mm along the z-axis. With this relatively large size, increasing the energy of the electron beam **106** is difficult because the number of windings and the amplitude of the current need to be significantly increased, and as a result a current amplifier of the system may need to be redesigned to meet these demands. The system **100** is also susceptible to external magnetic fields, which may result in manufacturing imperfections such as unplanned electron beam anomalies, beam excursions, and beam displacements.

FIGS. **2**A and **2**B are schematic diagrams of an exemplary EBM system **200**. FIG. **2**A shows the EBM system **200** without a shielding **214**, and FIG. **2**B shows the EBM system **200** with the shielding **214**. Besides the cathode **102** and the anode **104**, the system **200** further includes a focus coil assembly **202**. The focus coil assembly **202** is configured to focus the electron beam **106** generated by the cathode **102** and the anode **104**. The depicted focus coil assembly **202** includes two quadrupole magnets **302**. The thickness **203** of the quadrupole magnet **302** along the z-axis may be less than 10 mm, with similar operational parameters as the known focus coil assembly **108**, in which the focal length is approximately 750 mm for focusing an electron beam having energy of 60 keV with an operation current of 3 A. In some embodiments, the thickness **203** is approximately 8 mm. In some embodiments, the system **200** may include one quadrupole magnet **302**, three quadrupole magnets **302**, or any other number of quadrupole magnets **302** that enables the system **200** to function as disclosed herein. The system **200** further includes a deflection coil **204** configured to steer the electron beam **106** to travel to the vacuum chamber (not shown).

In the exemplary embodiment, the system **200** may further include the shielding **214** that surrounds the focus coil assembly **202** and the deflection coil **204** (see FIG. **2**B). The shielding **214** may be a cylindrical metal housing having a hole at each end that allows the electron beam **106** to enter into and exit from the shielding **214**. The shielding **214** may be in other shapes that enable the system **200** to function as disclosed herein. The shielding **214** protects the electron beam **106** from interference from nearby magnetic materials, such as motors. The shielding **214** also further limits stray field from spreading into the space outside the shielding **214**.

In operation, the electron beam **106** is generated by the cathode **102** and the anode **104**, and travels along the z-axis to the focus coil assembly **202**. The focus coil assembly **202** focuses the electron beam **106** to have a circular or near circular profile in the x-y plane. The electron beam **106** then is steered by the deflection coil **204** and travels to the vacuum chamber at a focused position **206** where a build plate (not shown) is located. For comparison, the distance between the deflection coil **110**, **204** to the build plate/the focused position **114**, **206** are kept the same, for systems **100** and **200**. Compared to the system **100**, the distance **212** that the electron beam **106** travels is approximately 860 mm in the system **200**, which is reduced by approximately 100 mm from the distance **112** for the system **100**. Thus, the size of the system **200** is greatly reduced as compared to the system **100**. The reduced beam travel distance **212** is enabled by the compact design of the quadrupole magnets **302** and the focus coil assembly **202** and reduced cross-talking between the quadrupole magnet **302** of the focus coil assembly **202** and the deflection coil **204**.

In some embodiments, the system **200** may further include a stigmator (not shown) configured to reduce astigmatism of the electron beam **106**, where the electron beam **106** has more than one focus point. The stigmator may be aligned with the focus coil assembly **202** and the deflection coil **204** along the z-axis, and positioned between the focus coil assembly **202** and the deflection coil **204**.

The focus coil assembly **202**, the deflection coil **204**, and the stigmator may be generally referred to an electron beam manipulation coil. In some embodiments, the system **200** further includes a control circuit that controls current flow through the electron beam manipulation coil. The control circuit includes an interface configured to receive the electron beam manipulation coil. The control circuit further includes a first switching device, a second switching device, and a third switching device. The first switching device is coupled to a first voltage source and is configured to create

a first current path with the first voltage source toward the electron beam manipulation coil. The second switching device is coupled to a second voltage source and is configured to create a second current path with the second voltage source toward the electron beam manipulation coil. The third switching device is coupled to a first side of the interface and is configured to allow conductance via the first current path and the second current path to the interface when the third switching device is in a closed position. The second and third switching devices are configured to create a third current path with the second voltage source when in respective open positions, the third current path having an opposite polarity with respect to the second current path. Related control circuits applicable to the present disclosure are described in greater detail in U.S. Pat. No. 8,712,015, which is incorporated herein by reference in its entirety.

In some embodiments, the system **200** further includes an inverse pulse control for eddy current abatement. Related inverse pulse controls applicable to the present disclosure are described in greater detail in U.S. Pat. No. 8,625,743, which is incorporated herein by reference in its entirety.

FIGS. **3**A and **3**B show an exemplary embodiment of the quadrupole magnet **302** that may be used with the system **200**. FIG. **3**A is a front view of the quadrupole magnet **302**, depicted as in the x-y plane. FIG. **3**B is a perspective view of the quadrupole magnet **302**. FIG. **3**C is a plot **320** of the magnetic field of the quadrupole magnet **302**.

In the exemplary embodiment, the quadrupole magnet **302** includes four magnetic poles **304***a*, **304***b*, **304***c*, **304***d*. Poles **304***a*-**304***d* may be referred to as a set of quadrupoles **304***a*-**304***d*. The poles **304***a*-**304***d* surround a beam cavity **306** through which the electron beam **106** travels. Each of the poles **304***a*-**304***d* includes a pole face **308** that faces the beam cavity **306** and an end **310** opposite the pole face **308**. The shape of the pole face **308** is convex in the exemplary embodiment. Poles **304***a*, **304***c* are positioned substantially along the x-axis and face each other at their respective pole faces **308**. Poles **304***b*, **304***d* are positioned substantially along the y-axis and face each other at their respective pole faces **308**.

In the exemplary embodiment, quadrupole magnets **302** are electromagnets, and quadrupole magnets **302** further include wires **312** winding around the poles **304***a*-**304***d*. To generate a magnetic field, current is run through the wires **312**. In some embodiments, the quadrupole magnets are permanent magnets. In the exemplary embodiment, poles **304***a*, **304***c* are both configured to have a first magnetic polarity at their respective pole faces **308**, while poles **304***b*, **304***d* are both configured to have a second magnetic polarity opposite the first magnetic polarity at their respective pole faces **308**. For each pole **304***a*-**304***d*, the pole face **308** and the end **310** each have opposite magnetic polarities. For example, for poles **304***a* and **304***c*, their pole faces **308** have a magnetic polarity of north, and their ends **310** have a magnetic polarity of south. In contrast, for poles **304***b* and **304***d*, their pole faces **308** have a magnetic polarity of south, and their ends **310** have a magnetic polarity of north. As a result, the quadrupole magnets **302** generate a quadrupole magnetic field. The magnetic polarity of the poles **304***a*-**304***d* may be changed by changing the direction of current flowing through the wires **312**. Further, the strength of the magnetic field generated by the wires **312** may be controlled and adjusted by adjusting the current and/or the number of windings of wires around poles **304***a*-**304***d*. Once the quadrupole magnet **302** has been manufactured, it may be difficult to change the number of windings without taking the quadrupole magnet **302** apart, but the strength of the magnetic field may be adjusted by adjusting the current flowing through the wires **312**.

In some embodiments, the quadrupole magnet **302** may be configured as a deflection coil **204**, in which quadrupole magnets **302** are configured to generate a dipole field. For example, in such a configuration, two neighboring poles have a first magnetic polarity at their pole faces **308** and the other two neighboring poles have a second magnetic polarity opposite the first magnetic polarity at their pole faces **308**. In another example, the current flowing through wires **312** for one pair of opposite facing poles is turned off, with the other pair of opposite facing poles having different magnetic polarities at their respective pole faces **308**.

The system **200** may further include a stigmator. In some embodiments, besides quadrupole magnets **302** in the focus coil assembly **202**, the system **100** further includes an additional quadrupole magnet **302** configured as a stigmator, where the quadrupole magnet **302** is oriented approximately 45° about the z-axis relative to the quadrupole magnet **302** in the focus coil assembly **202**. In other embodiments, the stigmator includes an octupole magnet (not shown). Compared to the quadrupole magnet **302**, which includes four poles **304***a*-**304***d*, the octupole magnet includes eight poles or two sets of quadrupoles **304***a*-**304***d*, with one set of quadrupoles **304***a*-**304***d* oriented approximately 45° about the z-axis relative to the other set of quadrupoles **304***a*-**304***d*. When an octupole magnet is used as a stigmator, the system **200** may include a quadrupole magnet **302** for focusing and an octupole magnet for astigmatism control.

In the exemplary embodiment, the quadrupole magnet **302** further includes a yoke **303**. To form a quadrupole magnet, the yoke **303** is coupled to the poles **304***a*-**304***d* at the ends **310** of poles **304***a*-**304***d*. The yoke **303** has a circular shape, which may be advantageous because a circular yoke **303** provides a uniform cross section, allowing a maximum area for magnetic flux, and reduces or eliminates magnetic flux concentration around the corners of a square or rectangular yoke **503** (see FIG. **5**A), where such magnetic flux concentrations affect the focus strength of the quadrupole magnet **502** (see FIG. **5**A) and create temperature hot spots in the yoke **503**. Further, compared to a square or rectangular yoke **503**, a circular yoke **303** is relatively easy to manufacture, reducing the manufacturing cost.

The yoke **303** is made of material that has a relatively high electrical resistivity and relatively high magnetic permeability. For example, at a room temperature, the resistivity of the material for the yoke **303** may be approximately 6×10^{-7} ohm·metre (Ω·m), which is 35 times higher than the resistivity of 1.7×10^{-8} Ω·m for copper. Permeability indicates the degree of magnetization that a material contains in response to an applied magnetic field. Compared to air, the permeability of the material for the yoke **303** is at least several hundred times to several thousand times higher such that the magnetic flux is contained in the yoke **303**. For example, if the relative permeability of air is 1, the relative permeability of the material for the yoke **303** is more than 1500 at a zero background field. Further, the relatively high electrical resistivity limits eddy currents caused by changes in the magnetic field. Eddy currents are opposite to the changes in the magnetic field and therefore reduce the generated magnetic field and the slew rate or the speed of switching the magnetic field up or down.

The yoke **303** may be made of laminated material, for example, laminated silicon iron. Laminated yoke material further increases the electrical resistivity of the material along the z-axis direction. In some embodiments, the yoke **303** is formed with a plurality of metallic layers with a

nonmetallic layer such as an epoxy positioned in between pairs of metallic layers and acting as an insulation layer. The plurality of metallic layers may be stacked along the z-axis. The nonmetallic layer serves as a barrier to eddy currents. With eddy currents reduced, the slew rate of transitioning the magnetic field is increased. Further, power loss during current transitions is reduced and a reduced current is needed to generate the same amount of magnetic field, which then reduces the demand on a current amplifier (not shown) that supplies current to the quadrupole magnet **302**, therefore reducing the cost of the amplifier and the system **200**. The number of metallic layers may be, for example, from ten to twenty layers. The thickness of the metallic layer may be approximately 1.27 mm (i.e., 1/20 inch). In one example, the yoke **303** is made of powder iron cores such as a molypermalloy powder (MPP), which is a mixture of iron powder with epoxy and other materials. In another example, the yoke **303** is made of soft ferrites, which are ceramic materials made by mixing iron oxide, metallic elements, or carbonates of metals such as manganese, zinc, nickel, or cobalt. Ferrites may be used for high-frequency applications.

In operation, using the yoke **303**, the magnetic field is relatively contained within the focus coil assembly **202**, and the magnetic flux is contained in the yoke **303** due to the relatively high permeability of the yoke **303**. With the magnetic flux contained within the focus coil assembly **202**, because of the effect of the yoke **303** on the pole face **308**, the magnetic field is concentrated at the pole faces **308** near where the electron beam **106** travels, and the magnetic field applied to the electron beam **106** is greatly increased, as compared to a solenoid focus coil assembly (e.g., the solenoid focus coil assembly **108** in system **100**) with the same dimensions. As a result, the size of the focus coil assembly **202** in the system **200** can be much less than a solenoid focus coil assembly. For example, the length of the focus coil assembly **202** in the z-axis may be approximately 10 mm plus the separation between quadrupole magnets, which may vary, as compared to the length of the solenoid focus coil assembly **108** being on the order of 100 mm. Further, compared to the known focus coil assembly **108**, the focus coil assembly **202** disclosed herein has improved performance. The focus coil assembly **202** has an increased slew rate due to the reduced inductance and reduced resistance.

FIG. **3**C shows a plot **320** of the magnetic field generated by the quadrupole magnet **302**, measured along a circle **318** having a radius of 20 mm from the center **319** of the quadrupole magnet **302**. In the plot **320**, the magnetic field is plotted as a function of the angle (θ) of the measuring location on the circle **318** relative to the positive x-axis, in other words, the angle between i) the line formed by the center **319** and the measuring location and ii) the positive x-axis. In FIG. **3**C, the curve **322** of the magnetic field in the plot **320** is smooth and resembles a function of cos 2θ, which is the magnetic field of an ideal quadrupole magnet. A curve **322** resembling the ideal function may be achieved by procedures such as changing the shape of pole faces **308**, the ratio of width over length of the pole **304***a-d*, and the location of wires **312** on the pole **304***a-d*. The smoothness of the curve **322** occurs because of the convex pole face **308**. A magnetic field having a smooth curve **322** causes less distortions in the electron beam **106** than a more turbulent magnetic field (see FIG. **5**B).

Because molecules in the air scatter the electron beam **106**, in an EBM system **100**, **200**, the electron beam **106** travels in vacuum instead. Accordingly, in the embodiments described herein, a vacuum tube **314** is used to enclose the beam **106**. The vacuum tube **314** may extend from the end of the beam tunnel **107** of the anode **104** to the end of the deflection coil **204** for the system **200** (FIG. **2**A). In at least some known systems, the vacuum tube is made of ceramic, which is relatively expensive and difficult to manufacture due to the manufacturing process of ceramic. Accordingly, in the exemplary embodiment, the vacuum tube **314** is made of metal, which is much cheaper and easier to manufacture than the traditional ceramic tube. The vacuum tube **314** also tolerates heat cycling better than a ceramic vacuum tube.

In operation, when the electron beam **106** travels through the beam cavity **306**, the quadrupole magnetic field generated by the quadrupole magnets **302** exerts a force on the electron beam **106** and adjusts the profile of the electron beam **106** in the x-y plane from an elliptical profile to a more circular profile.

Because of the modular configuration of the quadrupole magnet **302**, the EBM system **200** may include a focus coil assembly having two or more quadrupole magnets **302** to improve the profile of the electron beam **106**. In some embodiments, the focus coil assembly **202** includes two quadrupole magnets **302** (see FIGS. **2** and **4**A). The poles **304***a*-**304***d* of the two quadrupole magnets **302** are oriented 90 degrees about the z-axis relative to each other. In one example, one quadrupole magnet **302** is rotated 90 degrees about the z-axis relative to the other quadrupole magnet **302**. In another example, poles on each quadrupole magnet **302** that are aligned along the z-axis have opposite polarities from one another. The 90-degree rotation of the magnetic polarity may be accomplished by changing the direction of current flowing through the wires **312** wound around the poles **304***a*-**304***d*. When a pair of quadrupole magnets **302** are used in a focus coil assembly **202**, the current flowing through the quadrupole magnets **302** for generating a magnetic field may have substantially the same amplitude. In one example, current flowing through the first and second quadrupole magnets **302** is held in a substantially fixed ratio to one another during operation such that the shape of the focal spot on the target remains substantially constant when the current through the quadrupole magnets is changed. Related pairs of quadrupole magnets having current of a fixed ratio applicable to the present disclosure are described in greater detail in U.S. Pat. No. 9,153,409, which is incorporated herein by reference in its entirety.

In other embodiments, three quadrupole magnets **302** are used in a focus coil assembly **402** (see FIG. **4**B). In the embodiment shown, the poles **304***a*-**304***d* of the second quadrupole magnet **302** are oriented 90 degrees about the z-axis relative to the first and third quadrupole magnets **302**. The magnetic fields generated by the current provided to the first and third quadrupole magnets **302** may have substantially the same magnetic field strength as each other and approximately half of the magnetic field strength of the magnetic field generated by the current provided to the second quadrupole magnet **302**, in order to achieve a relatively circular profile for the electron beam **106**.

In addition, the modular configuration of the quadrupole magnet **302** reduces the complexity and different types of parts needed to assemble the system **200** by configuring the quadrupole magnet **302** as a deflection coil **204** in the system **200**. Two or more deflection coils **204** may be included in the EBM system **200** to adjust the direction of the electron beam **106** by positioning the deflection coil **204** at needed locations along the beam axis.

FIG. **5**A shows another exemplary quadrupole magnet **502**.

Compared to the quadrupole magnet **302**, the yoke **503** of the quadrupole magnet **502** has an angled, somewhat rect-

angular shape, and the pole faces **507** of poles **504***a*-**504***d* are concave. FIG. **5**B illustrates a plot **508** of the magnetic field of the quadrupole magnet **502** measured around a circle **518**. Similar to the plot **320**, in the plot **508**, the magnetic field is plotted as a function of the angle of the measuring location on the circle **518** relative to the positive x-axis. Comparing the plot **508** to the plot **320** for the quadrupole magnet **302**, the curve **510** in the plot **508** is not as smooth as the curve **322** in the plot **320**, and resembles the function cos 2θ less than the curve **322**. The bumps and deviations **512** in the curve **510** create distortion in the profile of the electron beam **106**.

The Quadrupole magnet **302**, **502** may be manufactured in two halves, with gaps **506** formed between the halves. The gaps **506** of the quadrupole magnet **502** are formed between neighboring poles. The gaps **506** of the quadrupole magnet **302** (not shown in FIGS. **3**A, **3**B, **4**A and **4**B) are formed adjacent the poles **304***a*-**304***d*. The quadrupole magnets **302**, **502** may be held together by clamps bridging the gaps **506** in some embodiments.

FIGS. **6**A-**6**D show the stray field of the solenoid focus coil assembly **108** (FIGS. **6**A and **6**B) as compared to the stray field of the focus coil assembly **202** including the quadrupole magnet **502** (FIGS. **6**C and **6**D). The stray field is the magnetic field present outside the associated focus coil assembly. For comparison, the stray field is measured at 75 mm away from the center of the focus coil assembly **108** or from the center of the quadrupole magnet **502** in the x-y plane as a function of the distance from the center in the z-axis direction. For solenoid focus coil assembly **108**, the stray field is measured along a cylinder **602** that has a radius of 75 mm in the x-y plane (FIG. **6**A). For the focus coil assembly **202**, the stray field is measured along a plane **604** that is parallel to the z-axis and perpendicular to the x-axis at x=75 mm or a plane **606** that is parallel to the z-axis and perpendicular to the y-axis at y=75 mm (FIG. **6**C). FIGS. **6**B and **6**D show the stray field measurements. In FIG. **6**B, the stray field (line **608**) of the solenoid focus coil assembly **108** is in the order of 6 gauss, while the stray field (lines **610**, **612**) of the focus coil assembly **202** is in the order of 0.25 Gauss, an approximately 24-fold reduction. As a result, the quadrupole magnets **302**, **502** may be placed close to each other and form a more compact focus coil assembly **202** than the solenoid focus coil assemblies **108**, thereby reducing the size of the EBM system **200**.

At least one technical effect of the systems and methods described herein includes (a) significantly reducing stray field from the focus coil assembly; (b) reducing eddy current in the focus coil assembly; (c) reducing dimensions of the focus coil assembly and the EBM system; (d) facilitating straightforward configurations of multiple focus coil assemblies and/or multiple deflection coils in the EBM system due to the modular configuration of the quadrupole magnets; (e) increasing flexibility in system configuration and reducing a number of parts in the system because a focus coil assembly may be used as a deflection coil; (f) providing shielded focus coil assemblies and deflection coils that protect the electron beam from exterior interference; and (g) reducing cost and manufacturing complexity of a metal vacuum tube for containing the electron beam.

Exemplary embodiments of systems and methods of focusing and steering an electron beam are described above in detail. The systems and methods are not limited to the specific embodiments described herein but, rather, components of the systems and/or operations of the methods may be utilized independently and separately from other components and/or operations described herein. Further, the described components and/or operations may also be defined in, or used in combination with, other systems, methods, and/or devices, and are not limited to practice with only the systems described herein.

Although specific features of various embodiments of the invention may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the invention, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A system for melting, sintering, or heat treating a material, said system comprising:

a cathode;

an anode, said cathode and said anode configured to generate an electron beam; and

a focus coil assembly comprising:

a quadrupole magnet comprising:

first, second, third, and fourth poles spaced apart from each other and surrounding a beam cavity through which the electron beam travels, each of said first, second, third, and fourth poles comprising a pole face proximate the beam cavity and an end opposite said pole face, said first and third poles aligned along an x-axis and configured to have a first magnetic polarity at their respective pole faces and a second magnetic polarity opposite the first magnetic polarity at their respective ends, said second and fourth poles aligned along a y-axis and configured to have the second magnetic polarity at their respective pole faces and the first magnetic polarity at their respective ends, wherein the x-axis is perpendicular to the y-axis; and

a yoke surrounding said first, second, third, and fourth poles and coupled to said first, second, third, and fourth poles at said ends of said first, second, third, and fourth poles.

2. The system of claim **1**, wherein said focus coil assembly comprises a first quadrupole magnet, wherein said focus coil assembly further comprises a second quadrupole magnet aligned with said first quadrupole magnet along a z-axis perpendicular to the x-axis and the y-axis, and wherein first, second, third, and fourth poles of said second quadrupole magnet are oriented 90 degrees about the z-axis relative to said first, second, third, and fourth poles of said first quadrupole magnet.

3. The system of claim **2**, wherein an amplitude of current provided to said first quadrupole magnet is in a substantially fixed ratio to an amplitude of current provided to said second quadrupole magnet during operation such that a size of a focal spot of the electron beam on a target remains substantially constant when currents through said first and second quadrupole magnets are changed.

4. The system of claim **2**, wherein said focus coil assembly further comprises a third quadrupole magnet aligned

with said first quadrupole magnet along a z-axis perpendicular to the x-axis and the y-axis , wherein said second quadrupole magnet is positioned between said first and third quadrupole magnets, wherein in operation, a first current is provided to said first quadrupole magnet, a second current is provided to said second quadrupole magnet, and a third current is provided to said third quadrupole magnet, wherein magnetic fields generated by the first and third currents have substantially the same magnetic field strength as each other and approximately half of the magnetic field strength of a magnetic field generated by the second current.

5. The system of claim **4**, wherein said third quadrupole magnet is aligned with said first quadrupole magnet along the z-axis, wherein first, second, third, and fourth poles of said third quadrupole magnet are oriented in the same direction about the z-axis relative to said first, second, third, and fourth poles of said first quadrupole magnet.

6. The system of claim **1**, further comprising a control circuit comprising:

an interface configured to receive an electron beam manipulation coil;

a first switching device coupled to a first voltage source and configured to create a first current path with the first voltage source toward the electron beam manipulation coil;

a second switching device coupled to a second voltage source and configured to create a second current path with the second voltage source toward the electron beam manipulation coil; and

a third switching device coupled to a first side of said interface and configured to allow conductance via the first current path and the second current path to said interface when said third switching device is in a closed position, wherein said second and third switching devices are configured to create a third current path with the second voltage source when in respective open positions, the third current path having an opposite polarity with respect to the second current path.

7. The system of claim **1**, wherein each of said pole faces of said first, second, third, and fourth poles is convex.

8. The system of claim **1**, further comprising a shielding surrounding said focus coil assembly.

9. The system of claim **1**, further comprising a metal vacuum tube sized to enclose the beam cavity.

10. The system of claim **9**, further comprising an inverse pulse control configured to abate eddy current.

11. The system of claim **1**, further comprising a stigmator, wherein said focus coil assembly is complemented by said stigmator.

12. The system of claim **11**, wherein said stigmator includes an octupole magnet including two sets of quadrupoles oriented approximately 45 degrees around the z-axis from one another.

13. The system of claim **11**, wherein said quadrupole magnet is a first quadrupole magnet, and wherein said stigmator comprises a second quadrupole magnet oriented approximately 45 degrees about the z-axis relative to said first quadrupole magnet.

14. The system of claim **1**, wherein said quadrupole magnet comprises a first quadrupole magnet, and wherein the system further comprises a deflection coil comprising a second quadrupole magnet configured to generate a dipole magnetic field.

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